CHEMICAL SCIENCES AND ENGINEERING DIVISION

BatPaC Model Software

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BatPaC – A Spreadsheet Tool to Design a Lithium Ion Battery and Estimate Its Production Cost

Lithium ion batteries are ubiquitous in consumer electronics today. Increasing demand for better performance – safer, lighter and smaller but with more capacity, with a longer life and lower cost – has prompted very significant investments in their development. The resulting progress has in turn spurred the deployment of this technology in transportation and stationary energy storage applications. Almost all car manufacturers have introduced commercial vehicles that use lithium ion batteries as their primary power source; some have announced timelines for discontinuing one or more product lines that use internal combustion engines and replacing them with battery electric vehicles.

The Battery Performance and Cost (BatPaC) model is a calculation method based on Microsoft® Office Excel spreadsheets that has been developed at Argonne for estimating the performance and manufacturing cost of lithium-ion batteries for electric-drive vehicles including hybrid-electrics (HEV), plug-in hybrids (PHEV) and pure electrics. The effort is being funded by the Vehicle Technology Office (VTO), which is part of the Energy Efficiency and Renewable Energy (EERE) office of the U.S. Department of Energy (USDOE). BatPaC was first developed in 2007, was subsequently peer reviewed, and it has served Argonne researchers and the greater battery community in studying the impact of material properties on performance at the pack level. With further developments the model now allows the design of cells and battery packs for automotive applications, to meet performance requirements (power, energy, recharge time), and estimates the cost of manufacturing the designed batteries. Since the cost depends on the materials, the design, and the manufacturing process, this bottom-up model/tool enables the user to study their effects. Designed for the lithium ion cell and battery researcher, BatPaC helps answer many “what-if” questions by being

1. Transparent in the assumptions made and the method of calculation
2. Capable of designing a battery specifically for the requirements of an application
3. Constrained by the physical limitations that govern battery performance
4. A bottom-up calculation approach to account for every cost factor

The tool enables access to a broad range of users and to facilitate transparency about the many input parameters. Some of the input parameters in the spreadsheet use values and equations that

are derived from external sources such as experiments or correlations from experimental/published data, transport or process models, and industry feedback on costs and manufacturing procedures.

The cell design in BatPaC assumes rectangular stiff pouches enclosed in modules that are further packaged within a pack enclosure. The assigned dimensions result in a more compact design than in vehicle batteries now being produced, but this high degree of compactness is anticipated to be

achievable in future commercial batteries. The price of materials is based on our best estimate at the time of a version release. The cost factors of installed capital equipment, labor, and manufacturing floor space (loaded with overhead costs) for each step in the manufacturing process are based on those in a baseline plant with a capacity of 8 GWh per year. The economies of scale or projections for the future (when larger plants will be in production) are calculated for each step in the process with equations[1] of the form,

Eq (1) Cost for A = Cost for B [(Throughput in step for Plant A) / (Throughput in step for Plant B)] ^{p}

The cost of each of the items for each step in the process is calculated by comparing the cost to that of the baseline plant (B) and allowing for the difference in the throughput for that step in the process. The value of the exponent, *p*, varies with each cost item and for each processing step.

Validation of the input material and capital costs are difficult to achieve as few values are publicly available. We therefore rely, to a large extent, on private communications[2] from equipment manufacturers, materials suppliers, cell manufacturers, and original equipment manufacturers (OEM). Variation does exist amongst the communicated values and after making our best estimate of the correct values, we have assigned accuracy limits to the final cost estimates. While the largest uncertainty in calculated values will exist in point cost estimates, the most instructive information may be gained by examining ranges in parameter values and relative changes between material properties.

The algorithm for the design of the battery pack is based on meeting the requirements for power and energy storage, and the recharging time in the case of all-electric vehicles (EV) or plug-in hybrid vehicles. The energy storage requirement determines the amount of electrode materials required, based on the specific capacity of the two electrode materials and the cell voltage. The cell area determines the cell resistance and therefore the power achievable. The model solves the equations to determine the smallest cell area (or maximum electrode thickness) that can satisfy the power and charge time requirement. The amount of inactive materials, such as current collectors, separators, cell containment, etc. are then calculated based on the cell area. The results from the material needs are then used to calculate the cost of production in a virtual plant with 16 stations (electrode mixing, coating, calendaring, etc.), where the costs of capital, labor, and floor space are calculated from the estimates made for the baseline plant

The cell design calculations are based on the selection of electrode couples from provided options with cathode active materials (NCA, NMCxyz, etc.) and anode active materials (graphite, lithium titanate). Default values of properties such as the density, porosity, cell voltage, impedance, etc., for these material combinations are automatically selected for an electrode couple; however, the user is able to select alternate values as appropriate. Similarly, the default cost contributors to the manufacturing plant are embedded in the appropriate worksheets and can be adjusted as needed.

The results generated from a set of calculations include the dimensions, mass, volume, and cost of the cell, module, and pack; with various breakdowns of the cost items.

Experts from all aspects of battery development have reviewed the model both privately and as part

of a formal peer-review process. The model was formally reviewed by a committee set up by the U.S. Environmental Protection Agency (USEPA) in 2011, and its continued development is periodically reviewed at the VTO Annual Merit Review meetings. The BatPaC model has been shared publicly via direct download or by request since 2012.

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[1] Perry's Chemical Engineers' Handbook, 9th Edition, edited by D.W. Green and M.Z. Southard, McGraw Hill Education, 2019.

[2] It is hoped that model users will be responsive by sharing their estimates of input values so that these can be aggregated and incorporated into BatPaC.

NOTES - GRPA 2018-21 NUMBERS

HTTPS://WWW.ANL.GOV/CSE/BATPAC-MODEL-SOFTWARE

Estimated Cost of EV Batteries 2018-2021

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2021 UPDATES

2021 modeled cost of a 300 mile EV battery pack: $133/kWh$_{Rated}$ ($157/kWh$_{Useable}$); Cell – $107/kWh$_{Rated}$ ($126/kWh$_{Useable}$)

The current cost estimate of $133 per kilowatt-hour of rated energy ($157/kWh$_{Useable}$), is derived using the peer reviewed and publicly available BatPaC battery cost modeling software developed at Argonne National Laboratory. (See attachment for an overview of the BatPaC model.) DOE-funded battery developers have submitted EV battery cost estimates, using the USABC battery cost model, in this same range. The cost is based on a production volume of 100,000 batteries per year, and is derived for batteries that are projected to meet DOE performance targets, including the 1,000 cycle life requirement.

Specific battery details are shown immediately below and in the following slides.

- NMC811 cathode, Graphite based anode
- 94 kWh$_{Rated}$, 80 kWh$_{Useable}$
- 200 kW
- 400 cells
- Slow charge - 56 minutes to charge from 15% to 95% SOC
- Plant production volume of 100,000 packs per year

2018–2021 comparison of battery specific energy and energy density

Based on developer input, the yearly cost estimates use
- **improved cathode materials (170, 175, 190, 200 mAh/g),**
- **thicker electrodes (70, 72, 72, 74 µm),**
- **N/P Ratio (1.25, 1.15),**
- **lower cost separator (1.3, 1.1, 1.0, 1.0 $/m²),**
- **cathode material price (21, 21, 22, 23 $/kg), and**
- **improved cell yield (83, 85, 87, 89%).**

NMCXXX-Graphite, 94 kWh$_{Rated}$, 80 kWh$_{Useable}$, 200 kW	2018	2019	2020	2021
Cathode Active Material	NMC622	NMC622	NMC811	NMC811
Pack Voltage, V	375	375	375	375
Cell Capacity, Ah	63	63	63	63
Specific Energy (Cell), Wh$_{Useable}$/kg (Wh$_{Rated}$/kg)	187 (220)	193 (227)	204 (240)	218 (256)
Specific Energy (Pack), Wh$_{Useable}$/kg (Wh$_{Rated}$/kg)	144 (169)	148 (174)	157 (185)	166 (195)
Energy Density (Cell), Wh$_{Useable}$/L (Wh$_{Rated}$/L)	433 (509)	446 (525)	469 (552)	501 (589)
Energy Density (Pack), Wh$_{Useable}$/L (Wh$_{Rated}$/L)	253 (298)	260 (306)	274 (322)	280 (329)

Useable Energy = 85% of Rated Energy

2018–2021 battery cost comparisons

Based on developer input, the yearly cost estimates use
- **improved cathode materials (170, 175, 190, 200 mAh/g),**
- **thicker electrodes (70, 72, 72, 74 µm),**
- **N/P Ratio (1.25, 1.15),**
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NMCXXX-Graphite, 94 kWh$_{Rated}$, 80 kWh$_{Useable}$, 200 kW	2018	2019	2020	2021
Cathode Active Material	NMC622	NMC622	NMC811	NMC811
Pack Voltage, V	375	375	375	375
Cell Capacity, Ah	63	63	63	63
Cell Cost, $/kWh$_{Useable}$	$160	$148	$138	$126
Cell Cost, $/kWh$_{Rated}$	$136	$126	$117	$107
Pack Price to OEM, $/kWh$_{Useable}$	$197	$185	$169	$157
Pack Price to OEM, $/kWh$_{Rated}$	**$168**	**$157**	**$143**	**$133**
Pack Price to OEM, $	$15,761	$14,814	$13,486	$12,552
Pack to Cell, $/$	1.24	1.22	1.22	1.25

Useable Energy = 85% of Rated Energy

Stepping from FY20 to FY21

Pack price dropped from \$143 to \$133 per kWh_{Rated}

CAM – Cathode Active Material, AAM – Anode Active Material, N:P – Negative to Positive Capacity Ratio
FY20 – BatPaC 4.0 Feb2020, FY21 – BatPaC 4.0 Dec2020

Benchmark EV Battery 1Apr2021 – BPC4.0 23Dec2020.xls   Waterfall Chart GPRA FY21 – 6Aug21.xlsx

Argonne

Design parameters and material price assumptions – 1

2020 vs. 2021 parameters, NMCXXX-Graphite, 94 kWh_{Rated}, 80 $kWh_{Useable}$ battery

Component	2019	2020	2021
Cathode Active Material (CAM)	NMC622	NMC811	NMC811
Cathode Active Material, mAh/g	170	190	200
Anode Active Material	Graphite	Graphite	Graphite
Anode Active Material, mAh/g	350	350	350
Negative to Positive Capacity Ratio (after formation)	1.25	1.25	1.15
Max. Current Density, mA/cm^2	6.0	6.0	6.0
Cell Voltage, V	3.750	3.751	3.751
Number of Cells (100S 4P)	400	400	400
Number of Modules	20	20	20
Charge time to Δ80% SOC, min	56	56	56
Cathode Thickness, μm	72	72	74
Cell Yield, %	85	87	89
Production Volume, packs/yr	100,000	100,000	100,000

Useable Energy = 85% of Rated Energy

Benchmark EV Battery 1July2019 – BPC3.1 28June2018.xls   Benchmark EV Battery 22July2020 – BPC4.0 19Feb2020.xls   Benchmark EV Battery 1Apr2021 – BPC4.0 23Dec2020.xls

Argonne

Design parameters and material price assumptions - 2

2020 vs. 2021 parameters, NMCXXX-Graphite, 94 kWh_{Rated}, 80 $kWh_{Useable}$ battery

Component	2019	2020	2021
Cathode Active Material (CAM)	NMC622	NMC811	NMC811
Cathode Active Material, \$/kg	\$21.00	\$22.00	\$22.80
Graphite, \$/kg	\$14.00	\$14.00	\$11.00
Electrolyte, \$/L	\$15.00	\$15.00	\$15.00
Separator, \$/m^2	\$1.10	\$1.00	\$1.00
Aluminum Current Collector, \$/m^2	\$0.40	\$0.40	\$0.40
Copper Current Collector, \$/m^2	\$1.20	\$1.20	\$1.20
PVDF, \$/kg	\$10.00	\$10.00	\$10.00
NMP, \$/kg	\$3.10	\$3.10	\$3.10

Useable Energy = 85% of Rated Energy

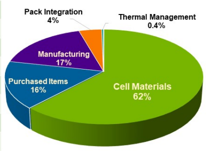
Benchmark EV Battery 1July2019 – BPC3.1 28June2018.xls   Benchmark EV Battery 22July2020 – BPC4.0 19Feb2020.xls   Benchmark EV Battery 1Apr2021 – BPC4.0 23Dec2020.xls

Argonne

Cell materials represent 62% of the 2021 pack cost

NMC811-Graphite, 80 $kWh_{Useable}$ (94 kWh_{Rated}), 200 kW, 400 cells, 100,000 packs/year, slow charge

Pack Cost to OEM, \$		\$12,552	% of Total
Pack Cost to OEM, \$/$kWh_{Useable}$		\$133	
Cell Materials		\$7,798*	62.1%
Purchased Items		\$2,045*	16.3%
Manufacturing		\$2,146*	17.1%
Electrode Processing	576		4.6%
Cell Assembly	451		3.6%
Formation Cycling, Testing, Sealing	532		4.2%
Module and Battery Assembly	273		2.2%
Cell Materials Rejection/Recycle	25		0.2%
Receiving and Shipping	227		1.8%
Control Laboratory	63		0.5%
Pack Integration (BMS, …)		\$522	4.2%
Thermal Management		\$40	0.3%



2021 Baseline

Benchmark EV Battery 1Apr2021 – BPC4.0 23Dec2020.xls

*includes overhead

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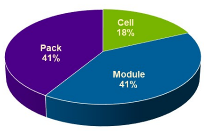
Cell Purchased Items are 18% of pack level purchased items, 2.8% of the pack cost

There are 400 cells and 20 modules in the pack

Purchased Items	\$1,917*	% of Total
Cell Purchased Items, \$/pack	\$349	18.2%
Module, \$/pack	\$780	40.7%
Pack, \$/pack	\$788	41.1%

Purchased Items include

- Cells: Terminal assemblies, Cell containment
- Module: Conductors, SOC regulator, terminals, gas release valve, module containment
- Battery Pack: Module connectors, compression plates, straps, pack terminals, bus bars, thermal system, pack jacket



2021 Baseline

*costs in the table exclude 6.7% overhead

Benchmark EV Battery 1Apr2021 – BPC4.0 23Dec2020.xls

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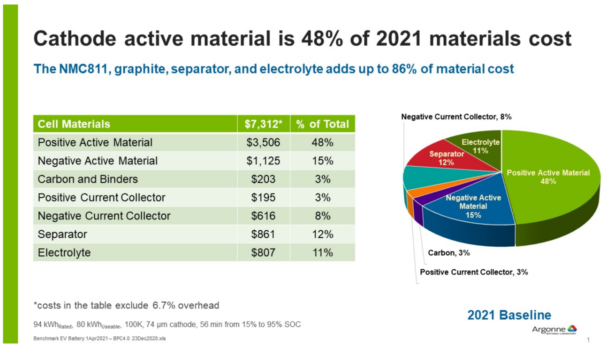

Cathode active material is 48% of 2021 materials cost

The NMC811, graphite, separator, and electrolyte adds up to 86% of material cost

Cell Materials	$7,312*	% of Total
Positive Active Material	$3,506	48%
Negative Active Material	$1,125	15%
Carbon and Binders	$203	3%
Positive Current Collector	$195	3%
Negative Current Collector	$616	8%
Separator	$861	12%
Electrolyte	$807	11%

*costs in the table exclude 6.7% overhead

94 kWh_{Rated}, 80 $kWh_{Useable}$, 100K, 74 μm cathode, 56 min from 15% to 95% SOC

Benchmark EV Battery 1Apr2021 – BPC4.0 23Dec2020.xls

2021 Baseline

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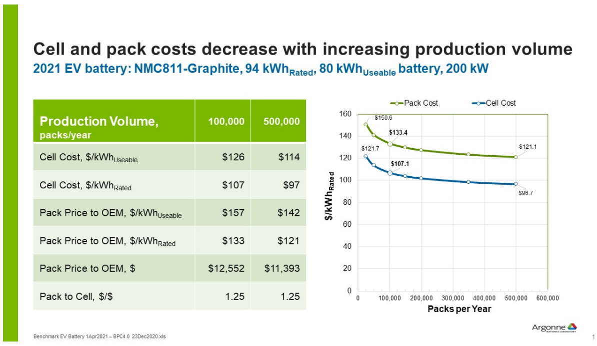

Cell and pack costs decrease with increasing production volume

2021 EV battery: NMC811-Graphite, 94 kWh_{Rated}, 80 $kWh_{Useable}$ battery, 200 kW

Production Volume, packs/year	100,000	500,000
Cell Cost, $\$/kWh_{Useable}$	$126	$114
Cell Cost, $\$/kWh_{Rated}$	$107	$97
Pack Price to OEM, $\$/kWh_{Useable}$	$157	$142
Pack Price to OEM, $\$/kWh_{Rated}$	$133	$121
Pack Price to OEM, $	$12,552	$11,393
Pack to Cell, $/$	1.25	1.25

Benchmark EV Battery 1Apr2021 – BPC4.0 23Dec2020.xls

Argonne

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